Paper 7

DIGITAL ELECTRONIC ENGINE CONTROL FAULT DETECTION AND ACCOMMODATION FLIGHT EVALUATION

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SUMMARY

The National Aeronautics and Space Administration (NASA), the U.S. Air Force (USAF), and the U.S. Navy (USN), along with other government agencies, are conducting various studies of existing and projected engine control systems to investigate the capabilities and performance of various fault detection and accommodation (FDA) schemes. These studies have made extensive use of analytical methods and simulations. Limited altitude testing has also been accomplished in support of these studies. With the advancement of the full-authority digital engine control systems, there has been an increasing desire to perform in-flight evaluations of FDA methodology for substantiating the predictions and facility results of the studies. Recent flight tests of the digital electronic engine control (DEEC) in an F-15 airplane have shown discrepancies between flight results and predictions based on simulation and altitude testing, and thus reinforce the need for flight evaluations. However, the difficulty of inducing realistic faults in flight has so far minimized flight testing of the FDA logic.

The DEEC is a full-authority, engine-mounted, fuel-cooled digital electronic control system that performs the functions of the standard F100 engine hydromechanical unified fuel control and the supervisory digital engine electronic control. The DEEC consists of a single-channel digital controller with selective input-output redundancy, and a simple hydromechanical backup control. The FDA features of the system are a significant portion of the control program. During the course of the recent flight program, the DEEC detected and accommodated two sensor faults, with no false failure indications.

An opportunity exists to conduct further flight evaluations of the DEEC FDA in the near future. The objectives of the program will be to induce selected faults and evaluate the resulting actions of the controller. Comparisons will be made between the flight results and predictions, as part of the evaluation. It is anticipated that the FDA data base will be expanded and techniques developed for safely evaluating FDA methodology in flight that may be useful on future programs.

This paper will describe the FDA methodology and logic currently in the DEEC system, and discuss the results of the flight failures that have occurred to date. The proposed flight program and anticipated results will be presented at this time.

ENGINE FAULT PROTECTION

The objective of the fault protection for the DEEC engine is to provide additional aircraft safety and operation in the event of an engine control system anomaly. This is accomplished through the FDA logic and the engine protection logic. The FDA provides three basic levels of engine operability in the event of an engine control system anomaly. The first level maintains normal operation of the engine with notification that a failure of a redundant parameter has occurred. The second fault accommodation level also maintains normal operation of the gas generator, but inhibits augmentor operation. This level is "instituted" for inputs which are critical to augmentor operation but not to the gas generator. Failure of parameters which are critical to the safe operation of the engine cause the system to automatically revert to the hydromechanical backup engine control. At each of these levels, the failures are annunciated through a caution light in the cockpit and specifically identified on one of the DEEC diagnostic words.

The engine protection logic provides an ultimate level of protection in addition to the FDA logic and the normal engine control scheduling. The logic is used to detect impending overspeeds and overtemperatures as a result of unpredicted multiple failures and automatically transfers the engine control to the hydromechanical backup system.

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DEEC Engine Fault Protection

Objective:

To provide for *additional* aircraft safety and operation in the event of an engine control system anomaly

- **Failure Detection and Accommodation "Levels"**
  1. **Maintain normal engine operation**
  2. **Loss of augmentation maintaining primary mode**
  3. **Automatic transfer to hydromechanical backup**

- **Engine Protect Logic:**
  Ultimate engine protection beyond FDA.

CONTROL SYSTEM

The DEEC system shown on the next page incorporates significant fault detection and accommodation logic. Part of the FDA methodology which is used in the DEEC system is reflected in the amount of redundancy of the system. Dual sensors and position transducers are used to achieve redundancy in key parameters such as engine speeds, temperatures, throttle position, gas generator fuel flow (WFGG), and rear compressor variable vane (RCVV). Redundant coils are present in the torque motor drivers for all actuators. Nonredundancy is retained in the less critical parameters of pressures, augmentor fuel flow, nozzle area, compressor inlet variable vane (CIVV), and aircraft Mach number.

The DEEC performs internal self-test and memory checks, processor instruction tests, interface tests, clock tests, and computational cycle-time tests. The built-in test (BIT) during normal engine operation includes: (a) read-only memory (ROM) check sum test as time permits during the execution of the control algorithm; (b) processor instruction checks as time permits; (c) input range checks: (d) torque motor coil testing to determine if the predescribed amount of current is flowing to each coil; (e) actuator loop test for torque motor integrity (as in (d)); (f) range checks to identify failed resolvers or actuators; and (g) loop dynamic checks for degradation of actuator response. These diagnostic test programs are provided for the DEEC controller to identify incipient anomalies before they can seriously affect the aircraft mission.

The selective input-output redundancy allows the system to maintain gas generator control with any single input-output failure. The control detects hard and soft failures of the dual sensors. Hard failures are declared when a sensor exceeds its maximum or minimum expected values. Soft failures are declared when the two signals disagree by more than a predetermined tolerance; the more conservative (safer) sensor value is then used. The pressure sensors (fan inlet static pressure (PS2), burner pressure (PB), turbine discharge total pressure (PT6M)) are not redundant, but the approximate value of one can be determined from the other two pressures. Failure of any nonredundant sensor will result in a loss of augmentation capability. Second failures of the dual sensors will result in an automatic transfer to the BUC, as will failures in the computer internal checks.

DEEC Control System Block Diagram

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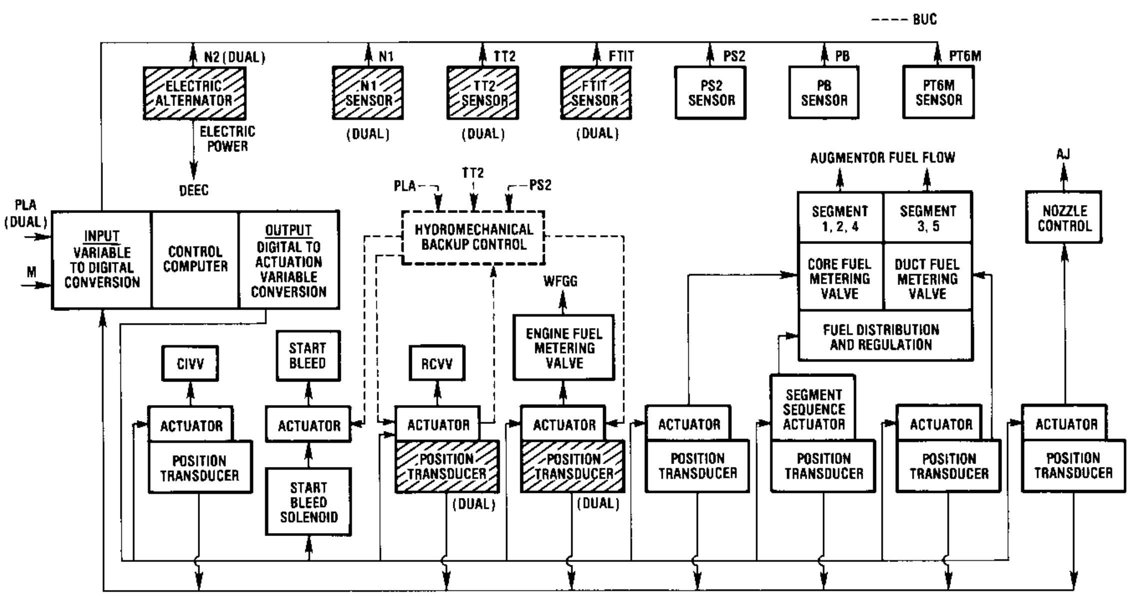

FAULT DETECTION AND ACCOMMODATION LEVELS

The fault detection and accommodation (FDA) shows that when the DEEC system is operating without faults, the level of activity of FDA is normal, as illustrated at the top of the figure. The next level occurs when the first system fault is detected and one of two possible fault accommodations can take place. One possibility is to accommodate the fault internally in the DEEC controller and the second is to transfer to the backup control system (BUC).

The decision to transfer to BUC is based on one of three possible detected conditions: (a) the DEEC controller has detected a fault which will not allow the controller to be in charge of the main core fuel flow or RCVV position; (b) the engine protection logic has detected a variable (fan rotor speed (N1), core rotor speed (N2), turbine inlet temperature (FTIT)) is either over the limit condition or its rate is such that the variable will reach an over-limit condition; or (c) a hardware independent fan speed (N1) circuit built into the DEEC controller detects an overspeed condition.

Other faults at this detection level drop down to the accommodation level (third level) where one of four operational conditions is selected, depending upon the fault condition. The operational accommodation, which has one-for-one hardware redundant fault replacement, yields a normal operating system. If the fault lies within the augmentor control of segment 3 or 5 (for example, duct metering valve fault), these elements are inhibited and the control system has an operational degradation. If the fault is more inclusive in the augmentor control, the engine augmentation function is inhibited with further reduction in operational capability. Should the synthesis of a control variable be required, then additional operational restriction is imposed, because the synthesized variable will be a conservative estimate of the replaced control variable. When operating in this level of accommodation (three levels down) and a second "like" fault occurs, the DEEC control automatically transfers operational control to BUC. The sensor failures which are detected by the DEEC FDA logic and the resulting actions are summarized in table 1.

DEEC Fault Detection/Accommodation

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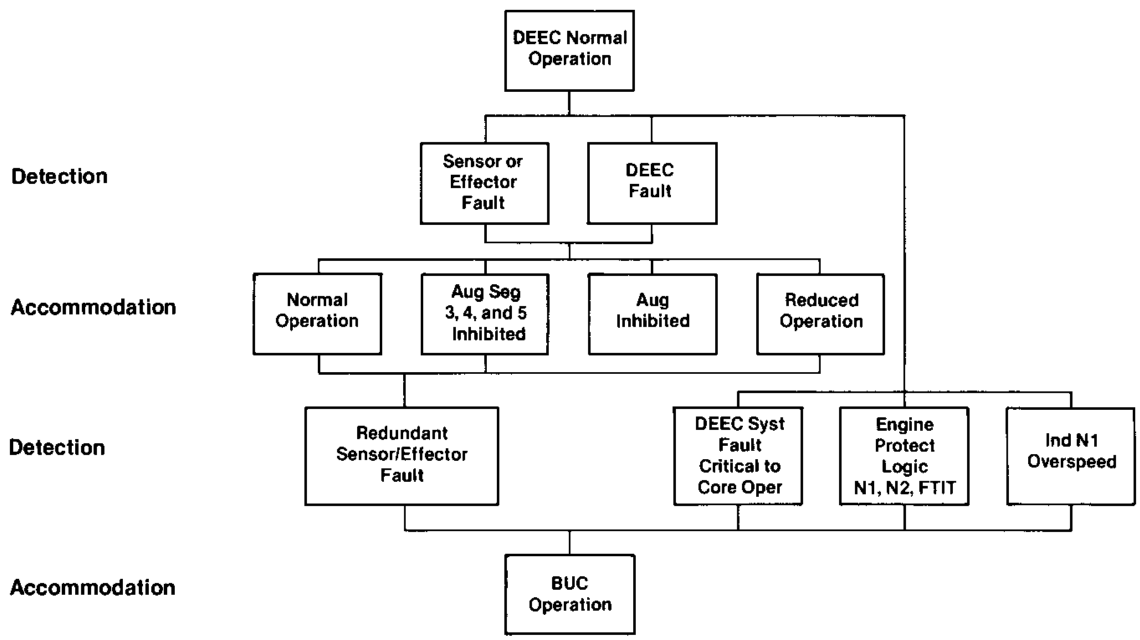

Table 1 FDA logic and actions

	Failure checks	Action
Redundant inputs:		
TT2, N1, N2, RCVV, FTIT, WFGG	Out of range Soft in range	Use in-range/BUC Use safer value
PLA	Out of range Soft in range	Use in-range/BUC Buc transfer
Single inputs:		
WFC, SVP	Out of range Open loop	A/B inhibited
WFD	Out of range Open loop	A/B limited to segment 2
PS2, PT6M	Out of range Soft in range	PS2 = PS2SYN A/B inhibited AJ trim inhibited PB soft fail-bypassed PS2 or PT6M, and PB fail-BUC
PB	Out of range Soft in range	PB = PBSYN A/B inhibited No stall detect logic PS2 or PT6M fail-BUC
TPS2, TPT6M, TPB	Out of range	Sub good temp sensors If all fail, fail pressure
Feedback sensors - single:		
CIVV	Out of range	CIVV full-cambered A/B inhibited
AJ	Out of range	AJ full closed A/B inhibited
Other		
Power (dual)	Out of range	BUC transfer
M.N.	Out of range	Mach = 0.15, limit set
Selftest (hardware)	Loss of interface	BUC transfer (critical loss)
Selftest (software)	Integrity check	BUC transfer

The functions of the PS2 sensor involve a full-time and part-time importance level as it is used in the fan speed request, nozzle request and trimming, and EPR request and feedback logic. A declared hard failure of the parameter causes the DEEC to use a synthesized PS2, based on corrected engine speed, engine inlet temperature, and burner pressure. Augmentor and nozzle trim functions of the engine are inhibited by the DEEC. In addition, the soft failure detection logic for burner pressure is bypassed as part of the FDA.

Burner pressure is classified as a full-time critical parameter since it is used in the scheduling of the core fuel flow and in the stall detection logic. It has a part-time criticality for the acceleration-deceleration limiting and limiting-engine burner pressure during high dynamic pressure (Q) conditions. As with PS2, detected sensor failures (hard or soft) cause a synthesized PB value to be substituted. There is no stall detection logic and augmentation is inhibited with this failure.

PT6M is used primarily at the intermediate and augmentor operation of the engine as part of the EPR feedback logic, blowout detection, and nozzle trimming functions. This parameter is not synthesized; hard failures which are detected result in elimination of augmentor operations and nozzle trim functions and the bypassing of the PB soft-fail logic.

DEEC Non-Redundant Sensors

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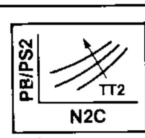
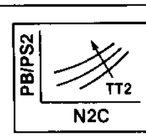
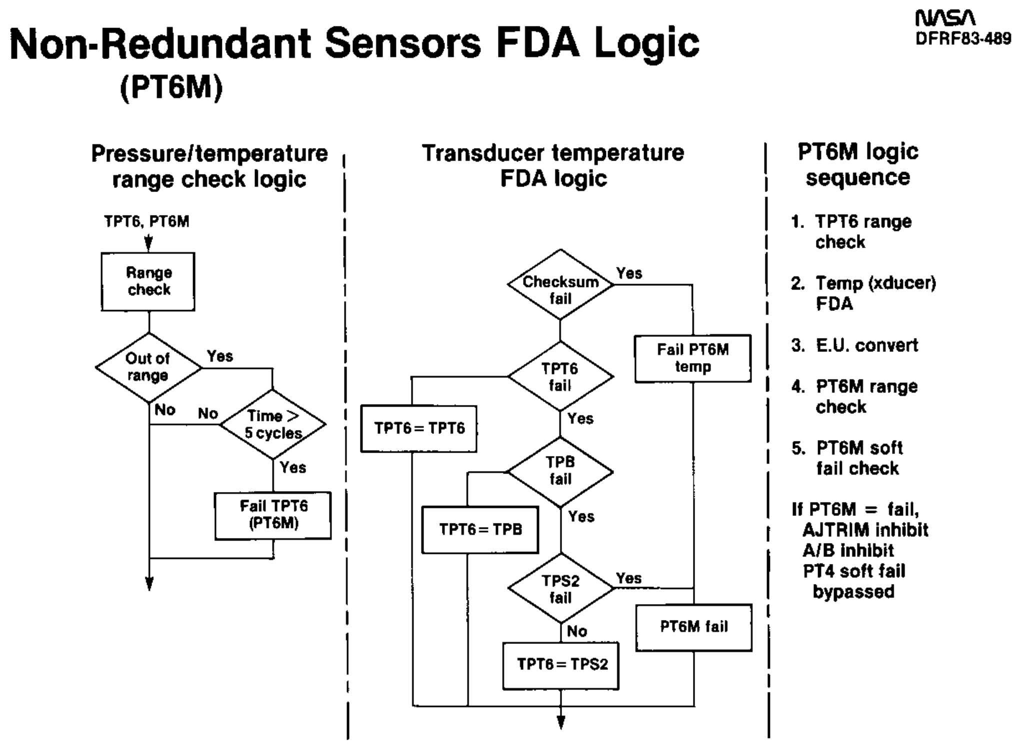
Function	PS 2 Inlet pressure	PB Burner pressure	PT6M Turbine discharge pressure
Full time—critical		• Core fuel flow scheduling • Stall detection	
Full time—important	• Fan speed req. • Nozzle area req.		
Part time—critical		• PB limiting (high Q) • Accel-decel limiting (full env.)	
Part time—important (Intermediate & augmented power)	• EPR req. • EPR feedback • Nozzle trim		• EPR feedback • Blowout detection • Nozzle trim
Synthesis	 $\rightarrow \frac{PB}{PS2}$ $\frac{1}{\frac{PB}{PS2}} \times PB = PS2SYN$	 $\rightarrow \frac{PB}{PS2}$ $\frac{PB}{PS2} \times PS2 = PBSYN$	None (Augmentation inhibited) (AJ trim inhibited)

NONREDUNDANT SENSOR LOGIC - PS2, PT6M

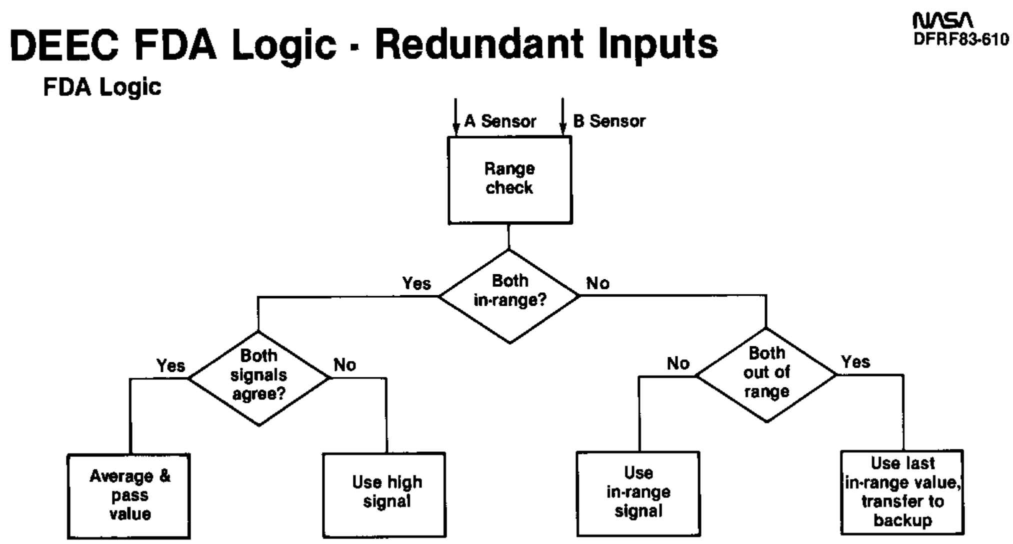
The FDA logic of the nonredundant pressure sensors (PS2 and PT6M) involve checks to be performed on the validity of the temperatures and pressures of the transducers, and the substitution of the transducer temperatures in the event of a temperature failure. The chart below shows the procedure for PT6M. A range check is made on the limits of the transducer pressure and temperature, with the sensor being declared failed after a specified number cycles. The detection and accommodation logic of the transducer temperatures consists of a substitution of the alternate transducer temperatures, since all three sensors are located together in the fuel-cooled electronic unit.

A check sum is made of the software locations, prior to this logic, to ensure there are no internal computer anomalies. If the three transducer temperatures or the check sum have failed, the affected pressure is declared failed and the system reverts to the BUC control mode. Following the transducer temperature FDA checks, the parameter is converted into engineering units and a range check, similar to the transducer temperature range check, is made. This particular logic sequence is utilized for the PS2, PB, and PT6M sensors. The PB sensor has an additional in-range logic check which compares the sensor value to the synthesized pressure value.



REDUNDANT SENSOR LOGIC - TT2

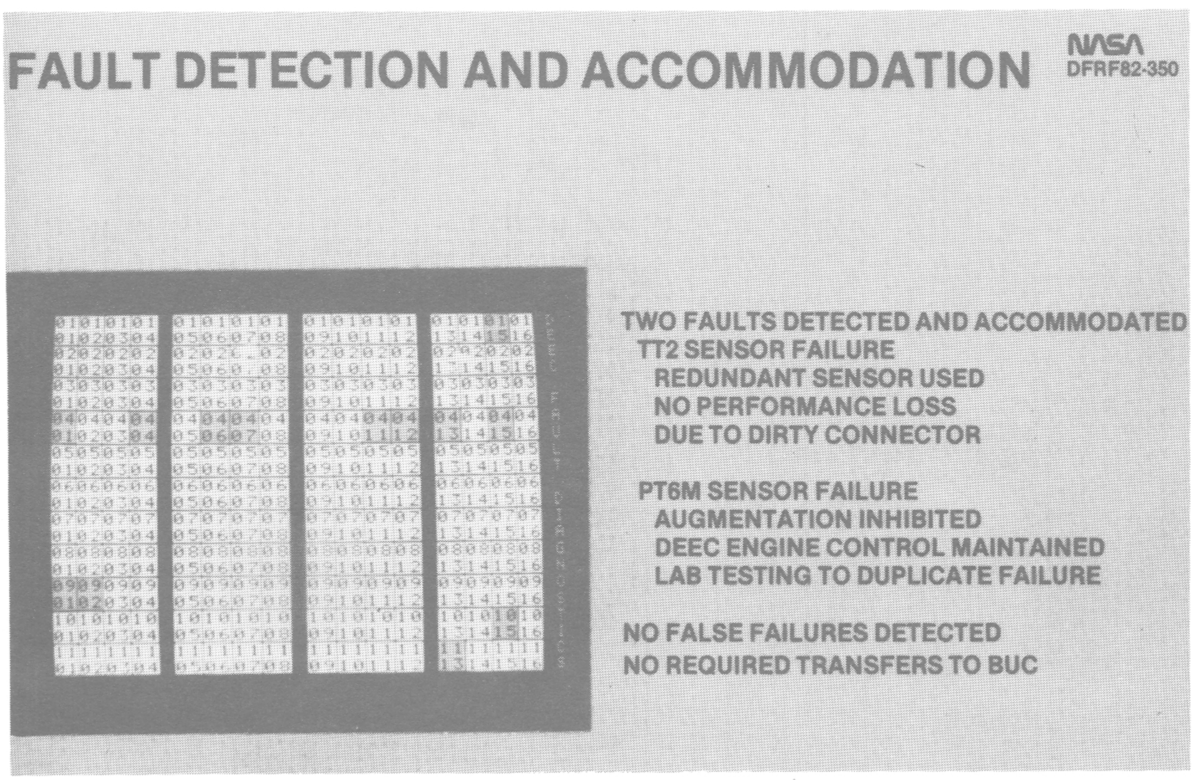
The fan inlet total temperature (TT2) parameter is one of the redundant sensor inputs used by the DEEC. The FDA logic checks for the redundant sensors are a range check for out of range and a check for agreement between sensors. If both sensors are in range, the sensors are compared. A disagreement between the signals by more than a predescribed tolerance causes the higher, or safer, value to be used. If either signal is out of range, the good value is used. With both signals out of range, an automatic transfer to the hydromechanical backup control is accomplished. Similar logic is used for the other dual sensors.



FDA - FLIGHT RESULTS

Extensive testing has been performed on the fault detection and accommodation (FDA) logic operation and ability to transfer to BUC under selected failure conditions. The closed-loop bench test allowed operation of hydromechanical and electronic components to be run while operating the engine computer simulation. This allowed testing of the FDA by intentionally introducing faults into the system without the risk of damaging an engine. Additional testing included sea level and altitude tests, and simulation testing of selected failures and resulting accommodation process.

The DEEC diagnostic words provide information on the health of the DEEC system. The words are displayed in the control room on the cathode ray tube (CRT) in a matrix format, as shown below. Failures which result in a transfer to the BUC mode are annunciated in the darker shade. Indication of other system faults are displayed on the light background. During the course of the DEEC flight test program, two faults were detected and accommodated. The first was a detected failure of the TT2 sensor which resulted in the use of the redundant sensor and no loss in performance. Post-flight inspection revealed the failure was due to a contaminated connector. The second failure involved the PT6M sensor, causing the nozzle trim feature and augmentor to be inhibited while DEEC engine control was maintained. The failure of the sensor was traced to the contamination of a PROM socket at the vibrating cylinder transducer. To date, there have been no false failures detected by the DEEC and no required transfers to BUC due to control system anomalies.



PT6M FAILURE DURING IDLE-TO-MAXIMUM TRANSIENT

The turbine discharge total pressure (PT6M) failure occurred during an idle-to-maximum transient at Mach 0.8 and 30,000 ft. The PT6M signal initially failed to a value of 92 lb/in^2, less than the upper limit of 110 lb/in^2. In response to this, the nozzle was driven open by the high PT6M signal in an attempt to accommodate the nozzle trim logic to hold EPR. The augmentor static pressure (PAB) trace shows the actual pressure change near the turbine discharge during the nozzle transient.When the PT6M sensor exceeded the 110 lb/in^2 maximum limit, the failure was flagged and the nozzle was commanded to the basic schedule value.

PT6M Failure During Idle-Max Transient
M = 0.8, 30,000 ft

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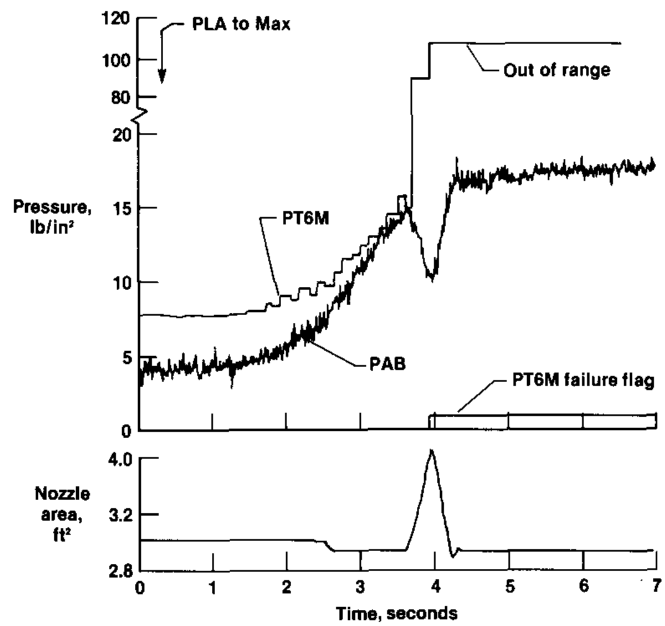

TT2 FAILURE

One of the two fan inlet total temperature (TT2) sensors failed following an acceleration to Mach 1.4 and 30,000 ft. The TT2 "A" sensor had been intermittent just prior to the data shown below, where it became a hard failure. The TT2 fail flag was set when the sensor exceeded the -110^{0} F limit. Since the detected failure was one of the redundant sensors, no performance loss was noted during the time the sensor had failed.

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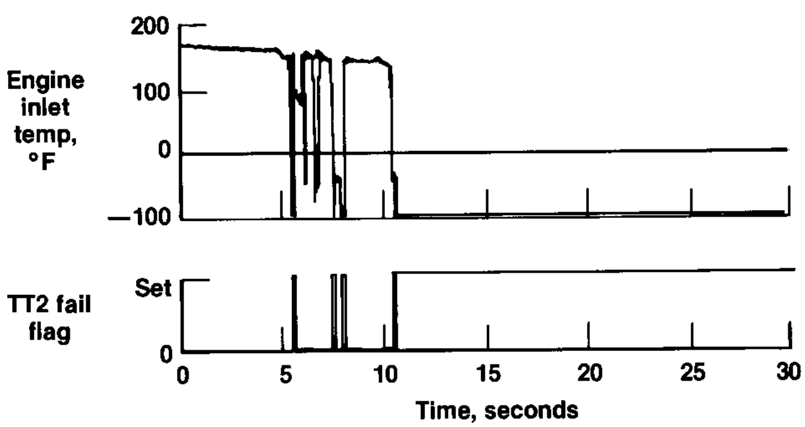
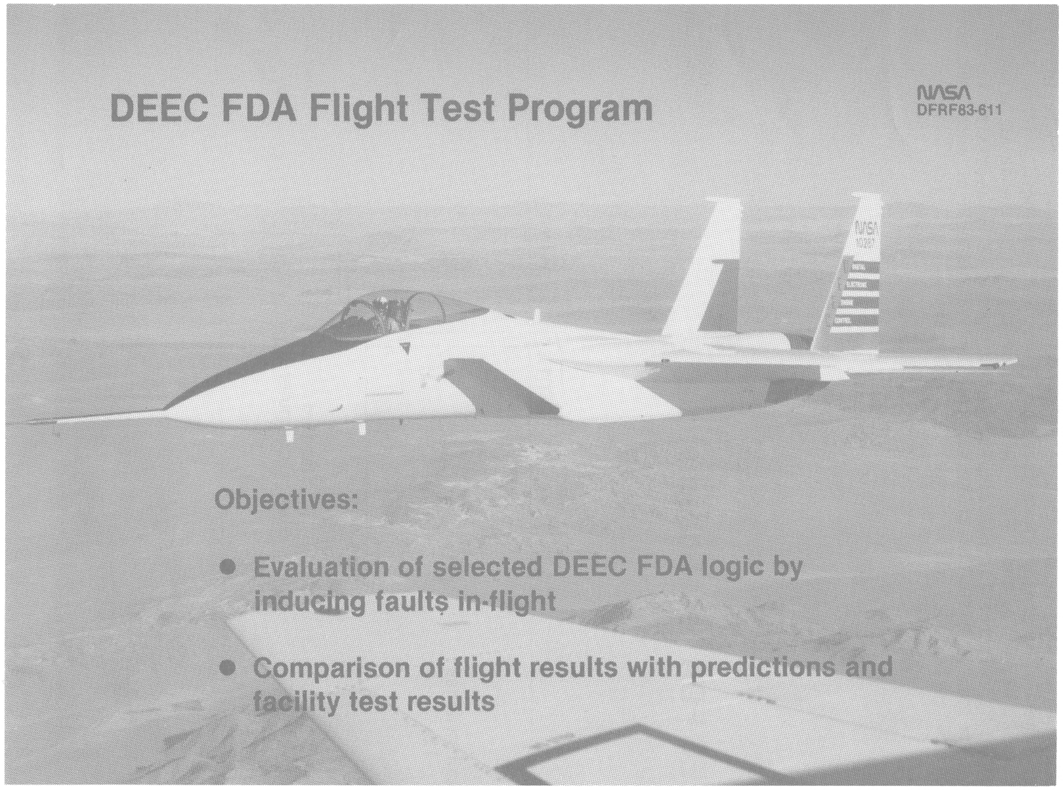
TT2 Failure
M = 1.4, 30,000 ft



FDA FLIGHT TEST PROGRAM

Early in the flight program, one of the ground rules was to abort the mission and return to base in the event of a failure. As more confidence was gained in the system and there was more interest in evaluating the failures in flight, contingency cards were made which contained selected testing to be accomplished in the event of a particular failure. The opportunity exists to use these procedures by inducing faults into the system and evaluating the outcome.

One of the objectives of the DEEC FDA flight program will be to evaluate the FDA logic for the PS2, PB, CIVV, and FTIT sensors by inducing faults in flight. The manner in which the faults are induced and the test techniques that will be developed will be applicable to other programs. The second objective will be the comparison of the flight results with predictions and facility results. Included in the comparison will be an evaluation on engine performance using synthesized values of PS2 and PB.


DEEC FDA Flight Test Program
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Objectives:
● Evaluation of selected DEEC FDA logic by inducing faults in-flight
● Comparison of flight results with predictions and facility test results

FDA TEST SCHEMATIC

The DEEC engine will be modified to allow switches and valves to be installed on the sensor lines. The sensor lines to be modified, and FDA logic which will be evaluated, are PS2, PB, CIVV, and FTIT. Selection of the failure mode to be induced will be controlled by switches in the cockpit. No changes will be necessary to the DEEC software. The configuration of these switches and valves will be such that the normal and fail-safe modes allow normal DEEC operation.

DEEC FDA Test Schematic

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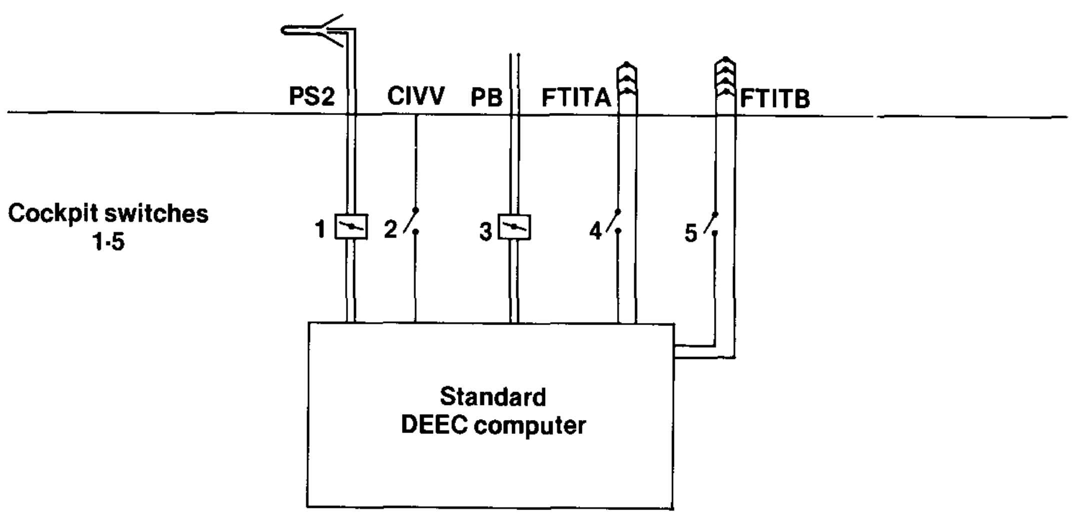

The test matrix shown contains all possible faults that may be induced during the flight program. The flight conditions selected represent the engine envelope and are based on simulation and facility data that are available for comparison. Steady-state tests and engine transients will be performed with the failures being induced before and during the maneuvers. Computer simulation will be used to evaluate each of these test conditions and induce failures prior to the actual flights to ensure there are no predicted adverse effects to the engine. Some of these points combine dual failures which may not be accommodated in the FDA logic and could result in an undesirable engine operating condition.

The FTIT failures will evaluate the redundant sensor logic. Sensor failures of PS2 and PB, both hard and soft, will exercise the nonredundant logic and pressure synthesis accommodation. The CIVV failures will be used to evaluate the open-loop actuator logic.

DFRF83-612

DEEC FDA Flight Test Matrix

Test Conditions

	Failure Modes	.8M, 30Kft	.8M, 50Kft	1.6M, 30Kft	1.6M, 50Kft	2.0M, 50Kft	Accel, 30K .8-1.6M	Accel, 50K .8-2.0M
FTIT	A - Fail	1-5			1-5			
	B- Fail		1-5					6
	Both - Fail	1-5	1-5		1-5	1-5	6	
PS2 & PB	PS2, Soft	1-5	1-5	1-5		1-5	6	
	PS2, Hard	1-5	1-5	1-5	1-5	1-5	6	
	PB, Soft	1-5	1-5	1-4	1-4	1-5		6
	PB, Hard	1-5	1-4	1-5	1-4	1-4		6
	PS2, Soft PB, Hard	1-5	1-5	1-4	1-5	1-4		
	PS2, Hard PB, Hard	1-5		1-4	1-5	1-4		
	PS2, Soft PB, Soft	1-5	1-5	1-4	1-5	1-4		
	PS2, Hard PB, Soft	1-5	1-5	1-4	1-5	1-4		
CIVV		1-4		1-4			6	

Legend
1 = Idle, steady-state
2 = Idle - I/M snap
3 = I/M, steady-state
4 = I/M - I snap
5 = I - max snap
6 = Fixed throttle

CIVV COMPARISON

Detection of a failure of the compressor inlet variable vane (CIVV) position feedback results in the CIVVs being commanded to the full-cambered position. This position, while it is a fail-safe mode, produces a significantly lower stall margin than the nominal schedule. The figure below illustrates the predicted amount of reduced stall margin at 30,000 ft with the CIVV failed to the full camber position. Because of the reduced fan stall margin, augmentor operation could result in stalls. Therefore, a CIVV failure inhibits augmentation. The flight test results with this failure will include nonaugmented transients and airplane maneuvers.

Effects of Failed CIVV on Fan Stall Margin

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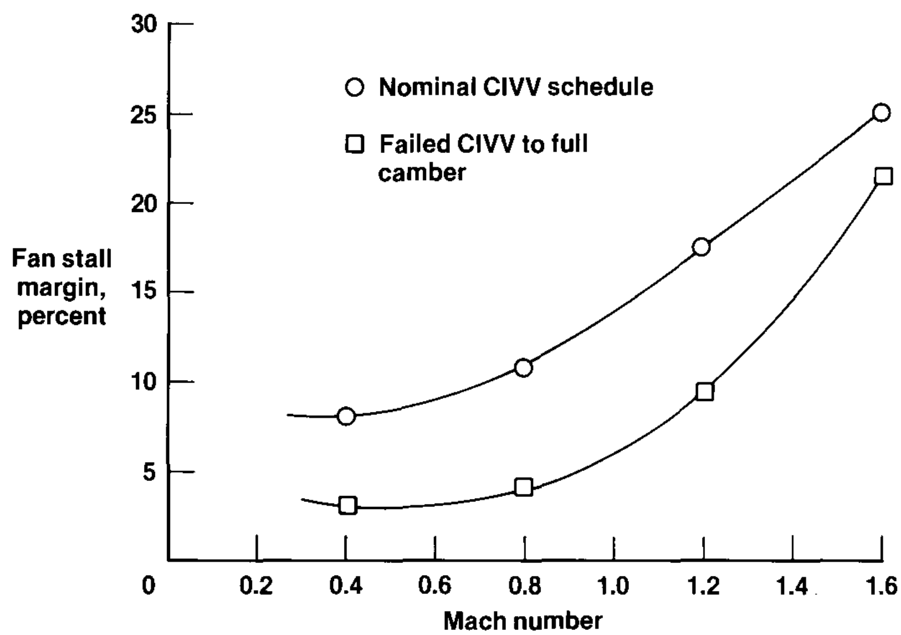
Results from DEEC Simulation
30,000 ft



PB COMPARISON

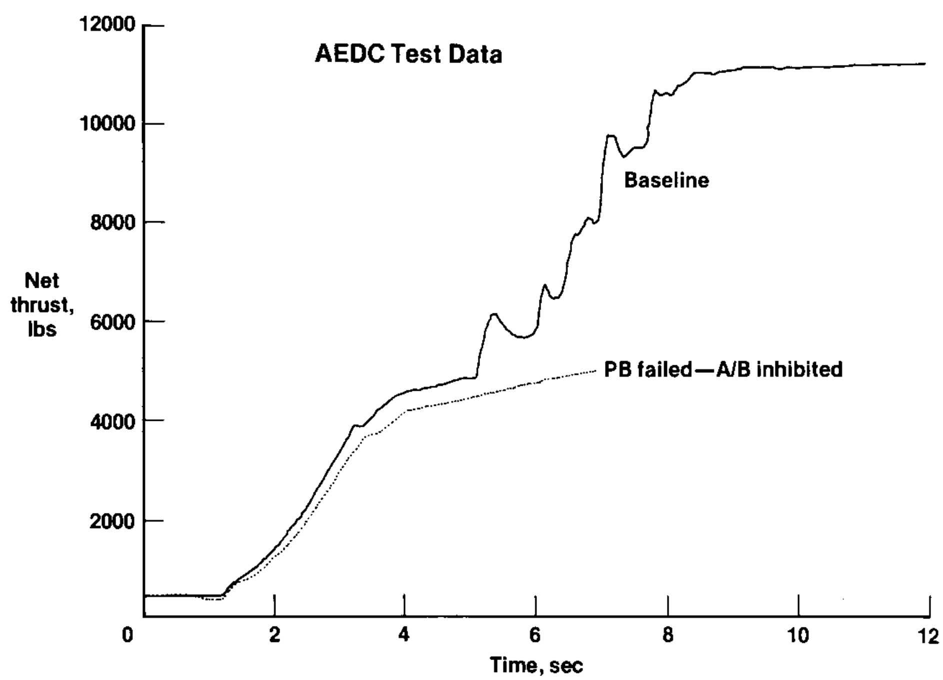
The figure below shows altitude facility data on the effect of a failed burner pressure (PB) sensor on the engine thrust during an idle-to-maximum snap at Mach 0.8 and 30,000 ft. The facility data shows the accommodation of the failure by inhibiting augmentation and scheduling the engine, using a synthesized burner pressure input. The flight results will be compared to facility data such as these, and include an evaluation of engine performance using a synthesized PB. The knowledge gained from the flight-program will be used to expand the existing data base of FDA information and include test techniques and validation processes of simulation and facility information.

Effect of Failed PB Sensor on Thrust

M = 0.8, 30,000 ft

Idle-to-Max Snap

NASA DFRF83-492



CONCLUDING REMARKS

The FDA methodology used in the DEEC is a fairly simplified parametric comparison process, but represents about 40 percent of the DEEC control program. The extensive testing and development of the FDA have included closed-loop bench tests, sea level and altitude engine tests, and computer simulation. This has resulted in a high level of confidence in the DEEC FDA logic. Successful fault detection and accommodation have been demonstrated with the flight failures of the PT6M and TT2 sensors. To date, there have been no false failures or required transfers to the backup control because of control system anomalies. The high degree of confidence in the DEEC system and the opportunity to expand the FDA data base to include additional flight data has made future flight evaluation of the DEEC FDA a highly desirable and realistic goal.

Summary

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- **DEEC FDA is a fairly simplified methodology, but represents a significant portion of the control program**
- **Testing of FDA included closed loop bench tests, sea-level and altitude engine tests, and computer simulation**
- **Flight failures of PT6 and TT2 demonstrated successful fault detection and accommodation**
- **There were no false failures or required transfers to BUC due to control system anomolies**
- **Further flight evaluation of the DEEC FDA is a highly desirable and realistic goal**